



US009405185B2

(12) **United States Patent**
Utzny et al.

(10) **Patent No.:** **US 9,405,185 B2**
(45) **Date of Patent:** **Aug. 2, 2016**

(54) **SHAPE METROLOGY FOR PHOTOMASKS**

(71) Applicant: **Advanced Mask Technology Center GmbH & Co. KG**, Dresden (DE)

(72) Inventors: **Clemens Utzny**, Dresden (DE); **Markus Bender**, Dresden (DE); **Christian Buerger**, Langebrueck (DE); **Albrecht Ullrich**, Dresden (DE)

(73) Assignee: **Advanced Mask Technology Center GmbH & Co. KG**, Dresden (DE)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 18 days.

(21) Appl. No.: **14/246,645**

(22) Filed: **Apr. 7, 2014**

(65) **Prior Publication Data**

US 2015/0286130 A1 Oct. 8, 2015

(51) **Int. Cl.**
G03F 1/36 (2012.01)
G03F 1/44 (2012.01)
G01B 11/02 (2006.01)
G01F 1/44 (2006.01)

(52) **U.S. Cl.**
CPC **G03F 1/36** (2013.01); **G01B 11/02** (2013.01);
G01F 1/44 (2013.01)

(58) **Field of Classification Search**

CPC G03F 1/36; G03F 1/144; G01B 11/02
USPC 430/5, 30
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2003/0233630 A1* 12/2003 Sandstrom G03F 1/144
716/50

* cited by examiner

Primary Examiner — Christopher Young

(74) *Attorney, Agent, or Firm* — Dicke, Billig & Czaja, PLLC

(57) **ABSTRACT**

A method of manufacturing a photomask includes forming a mask pattern with a critical mask feature on a photomask. Shape information which is descriptive for an outline of the critical mask feature is obtained from the photomask. The shape information contains position information identifying the positions of landmarks on the outline relative to each other. The landmarks may indicate local curvature extrema, points of inflexion, sharp bends in the curvature and/or local curvature-change maxima in the outline of the mask feature, respectively. The shape information may enable a shape metrology which is not completely based on rectangular approximations of mask features.

13 Claims, 13 Drawing Sheets

FIG. 1A

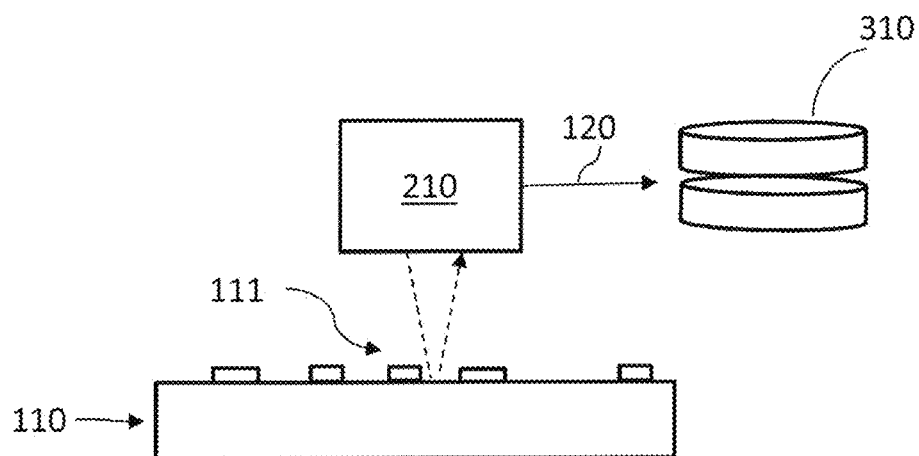


FIG. 1B

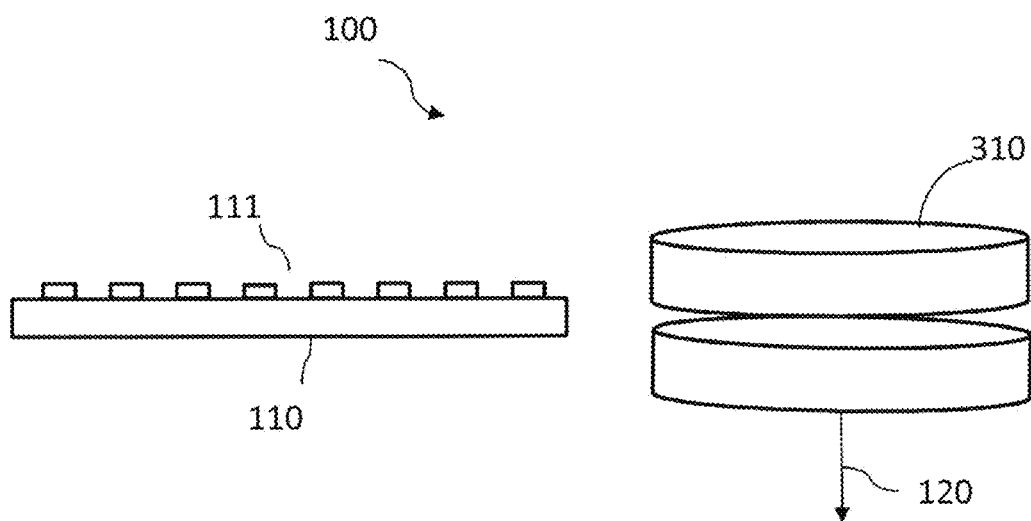


FIG. 1C

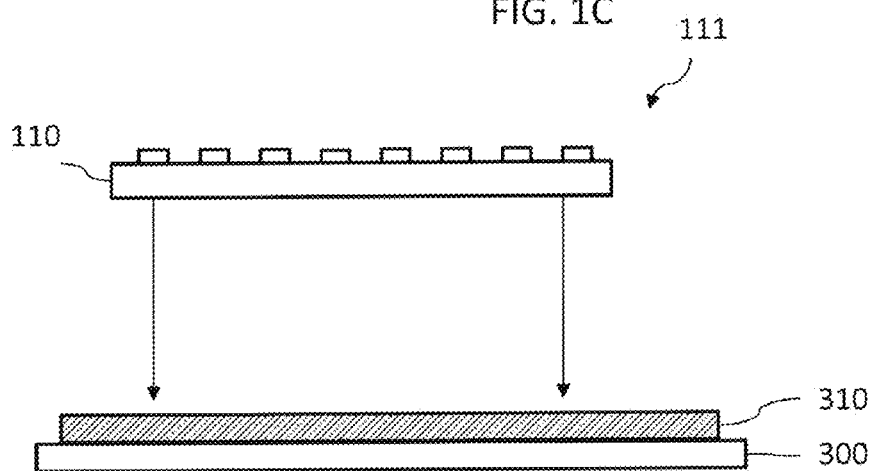


FIG. 1D

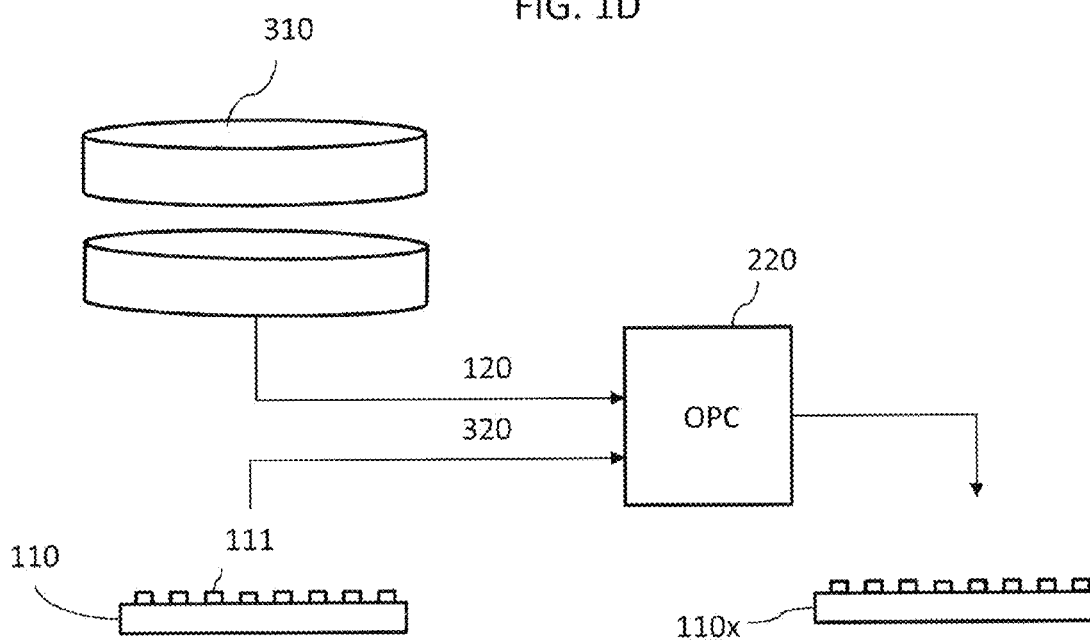


FIG. 2A

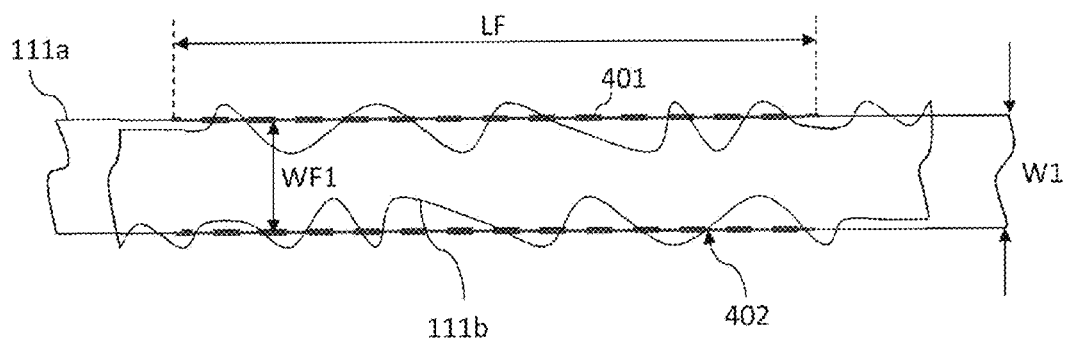


FIG. 2B

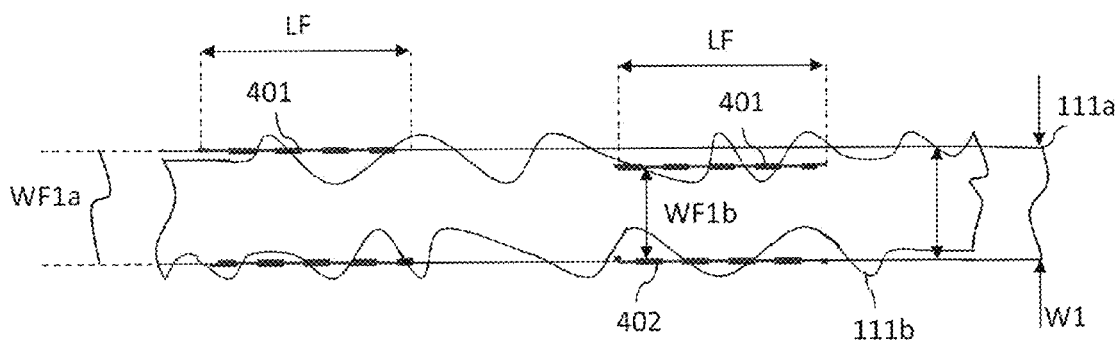


FIG. 3A

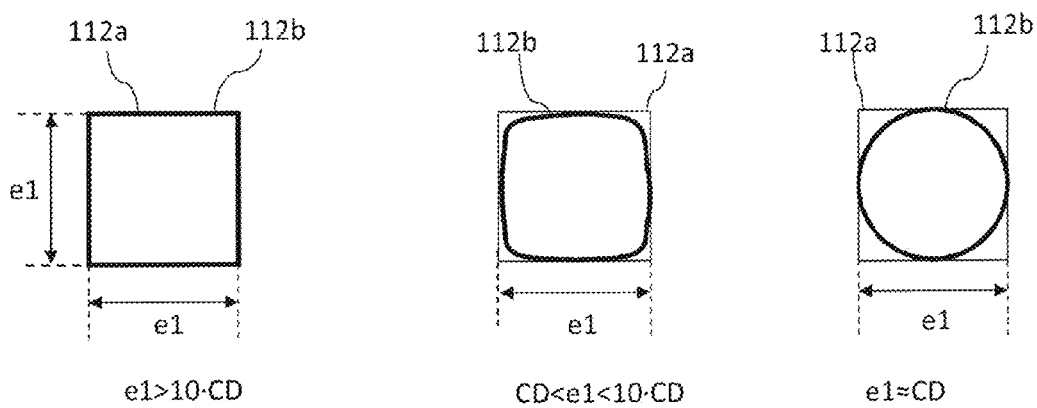


FIG. 3B

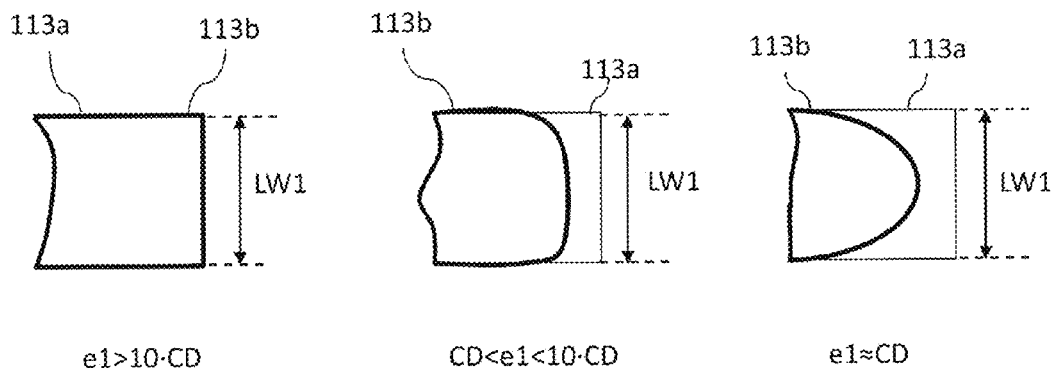


FIG. 3C

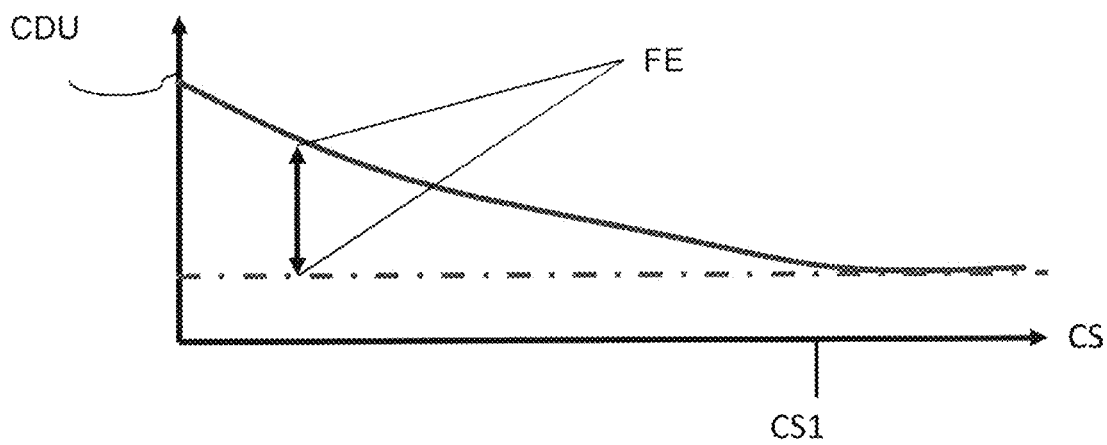


FIG. 4A

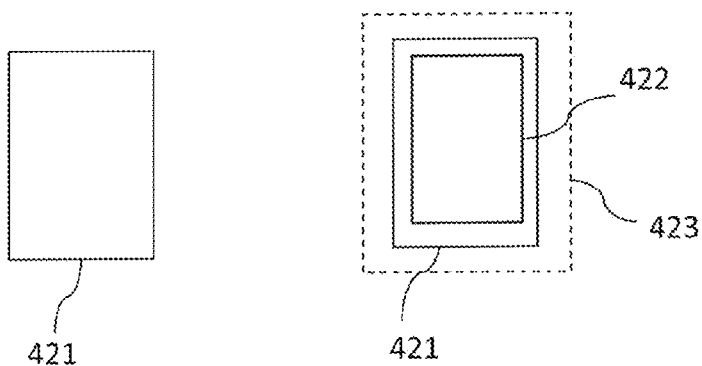


FIG. 4B

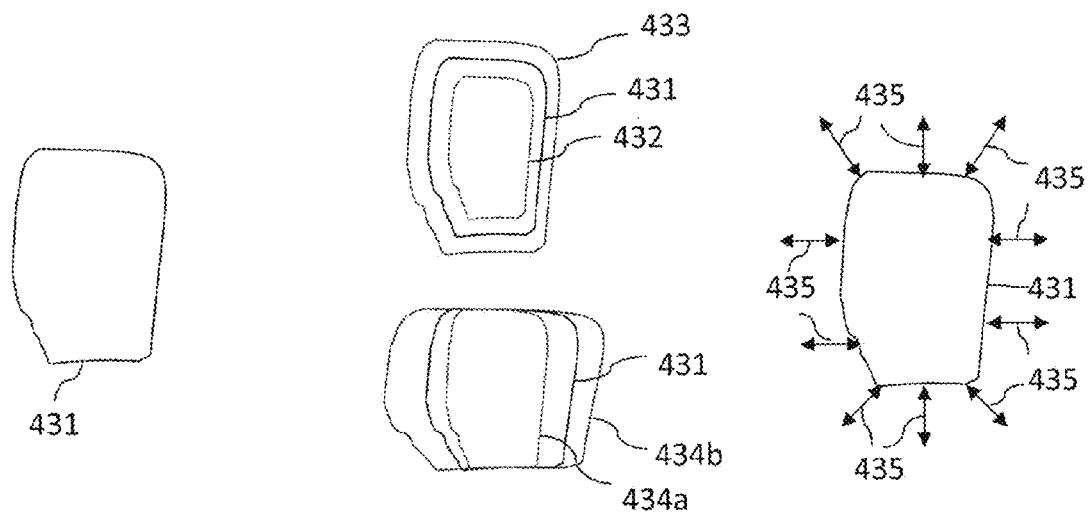


FIG. 5A

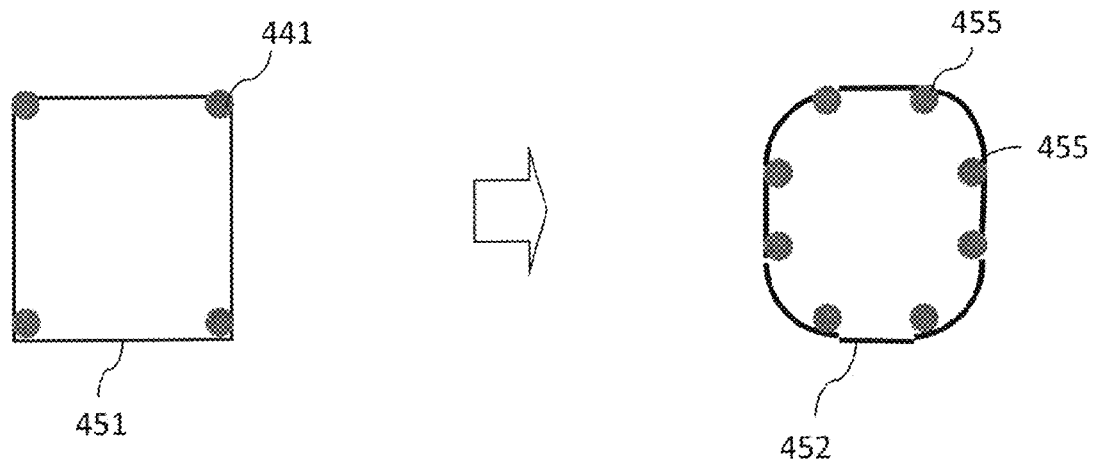


FIG. 5B

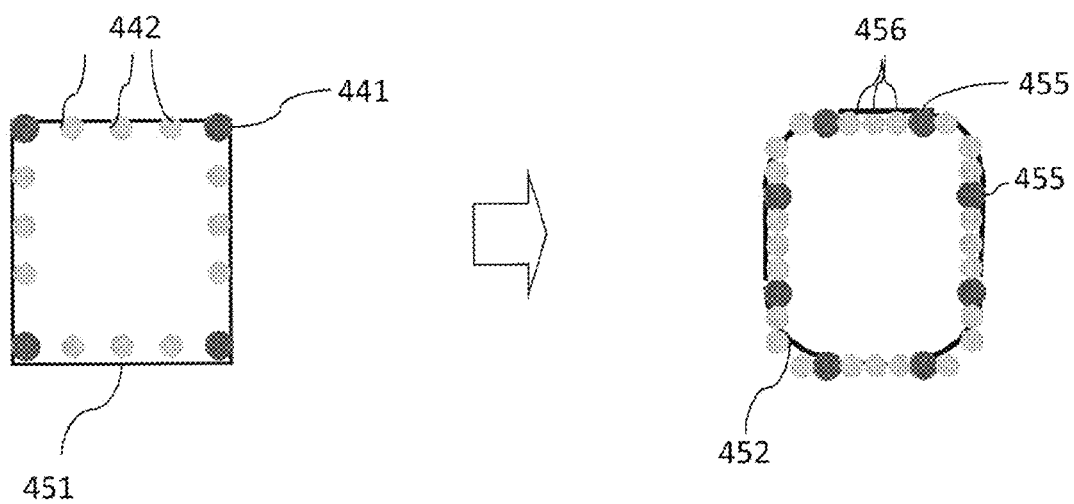


FIG. 5C

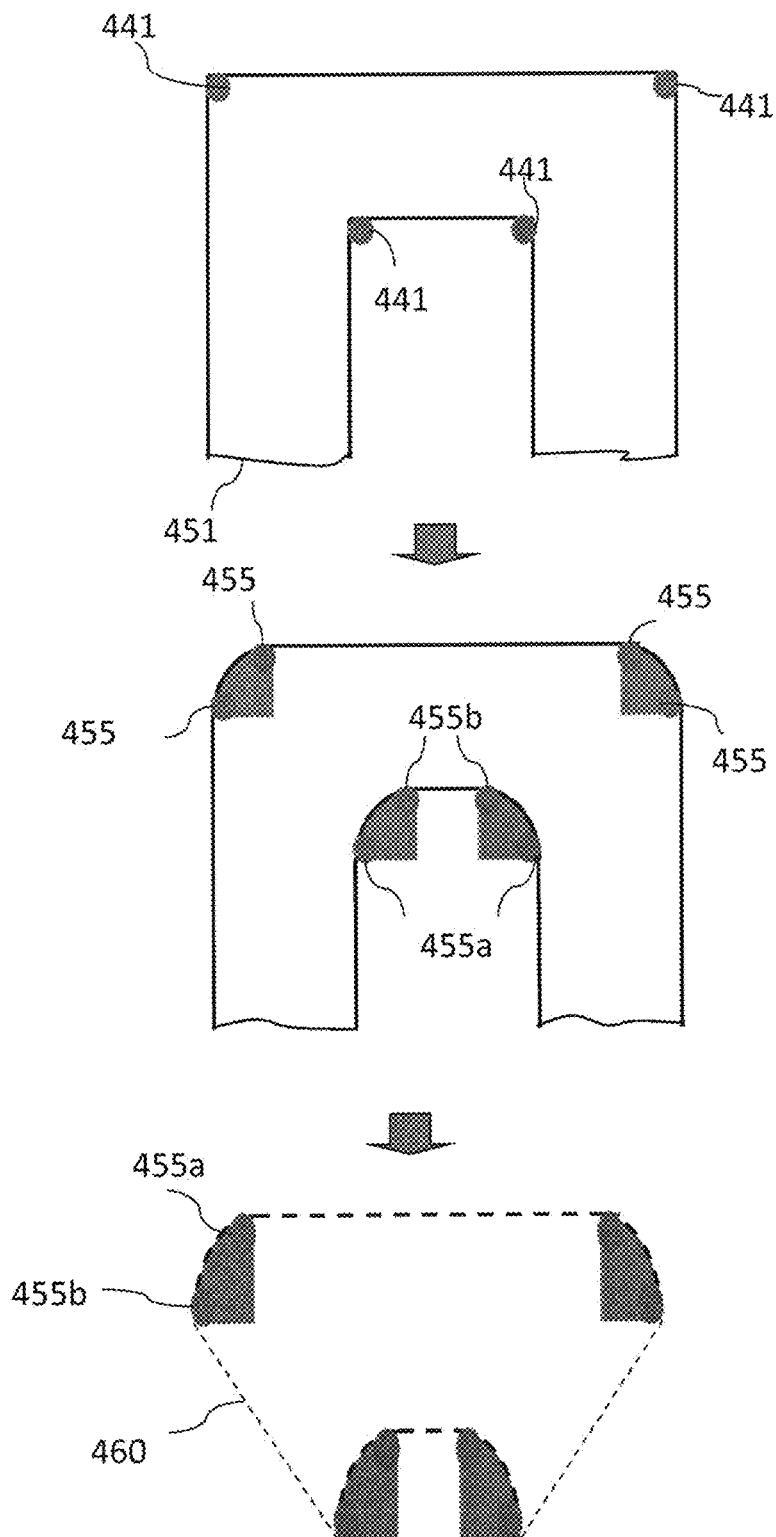


FIG. 6

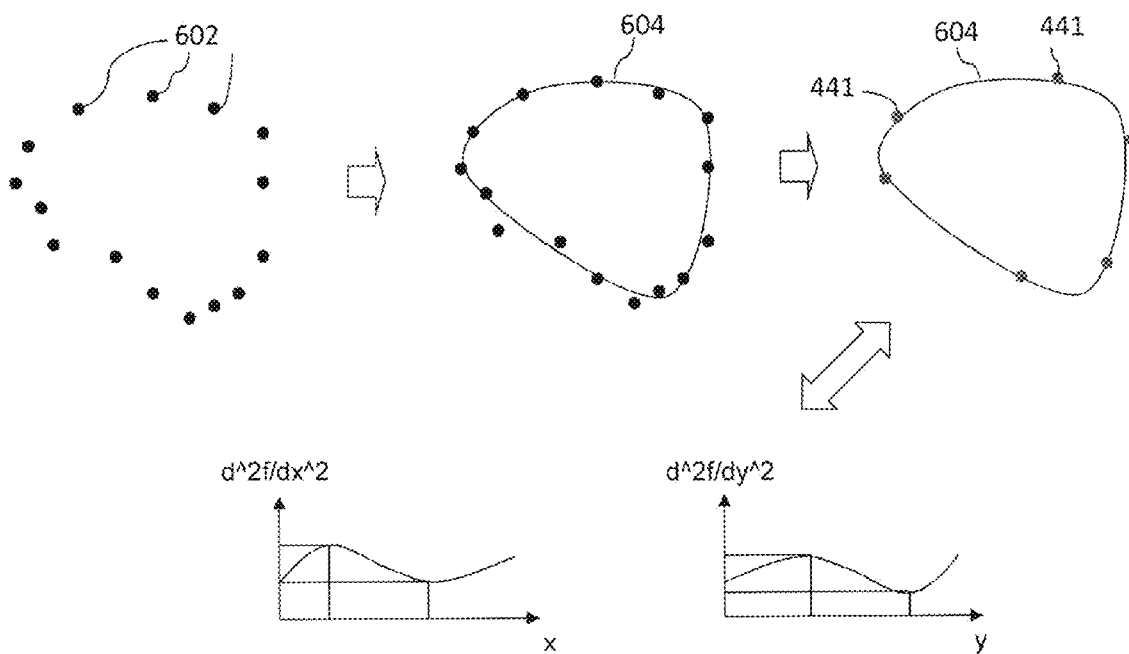


FIG. 7A

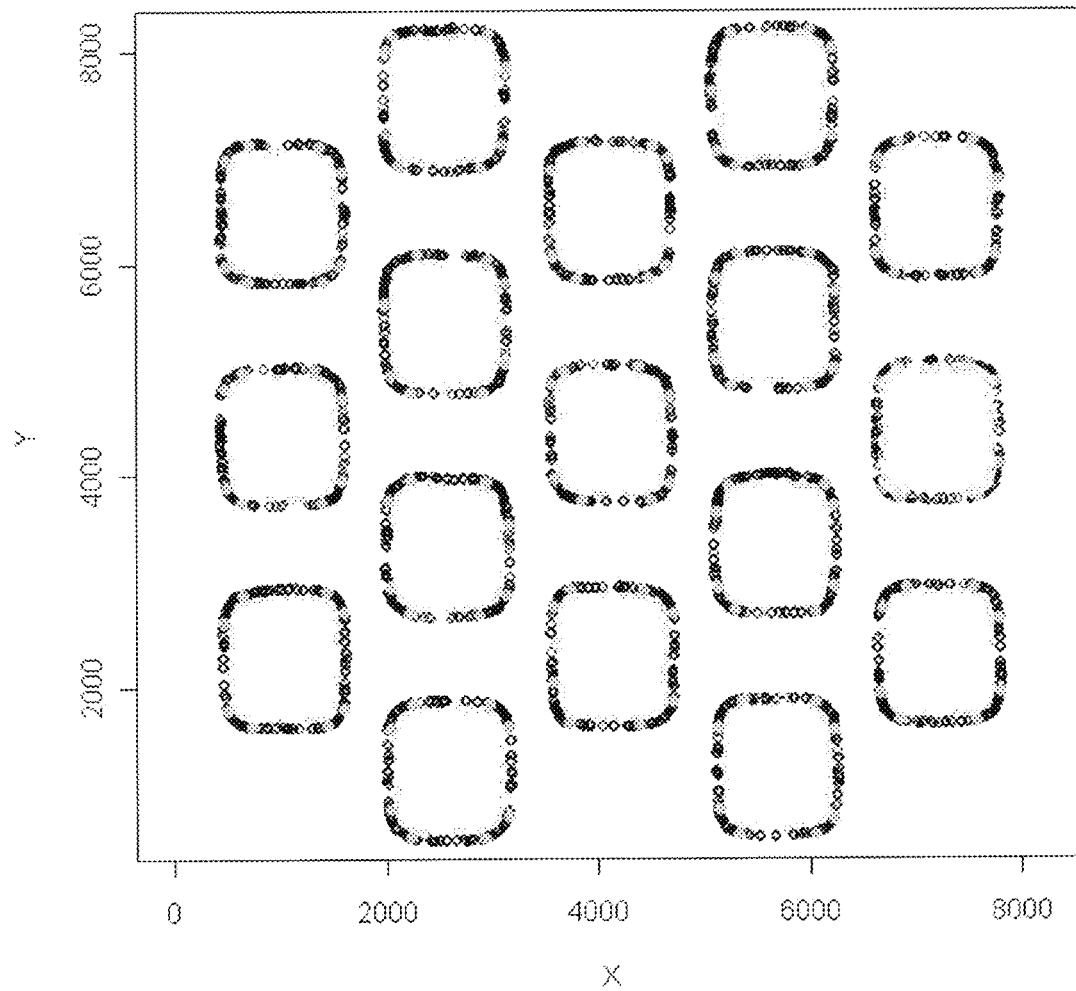


FIG. 7B

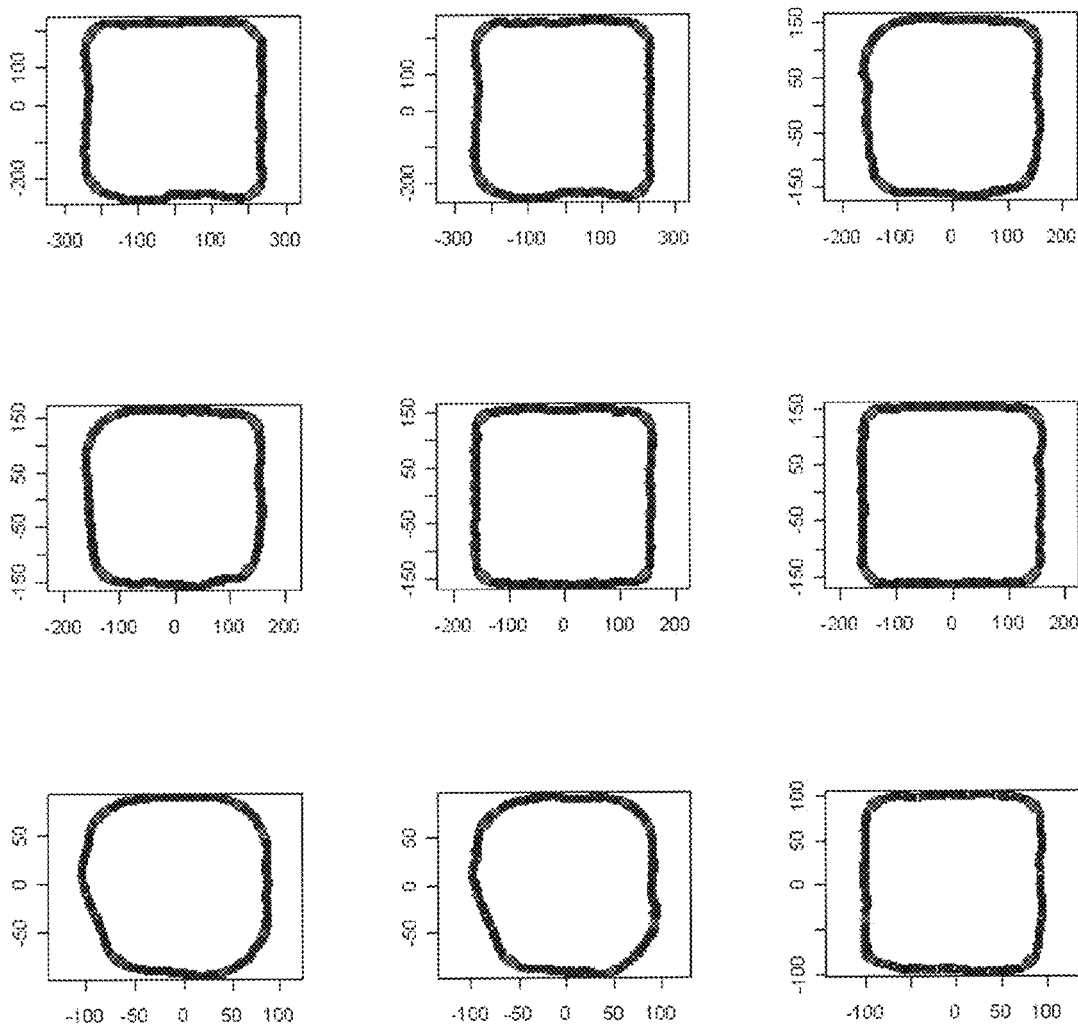


FIG. 7C

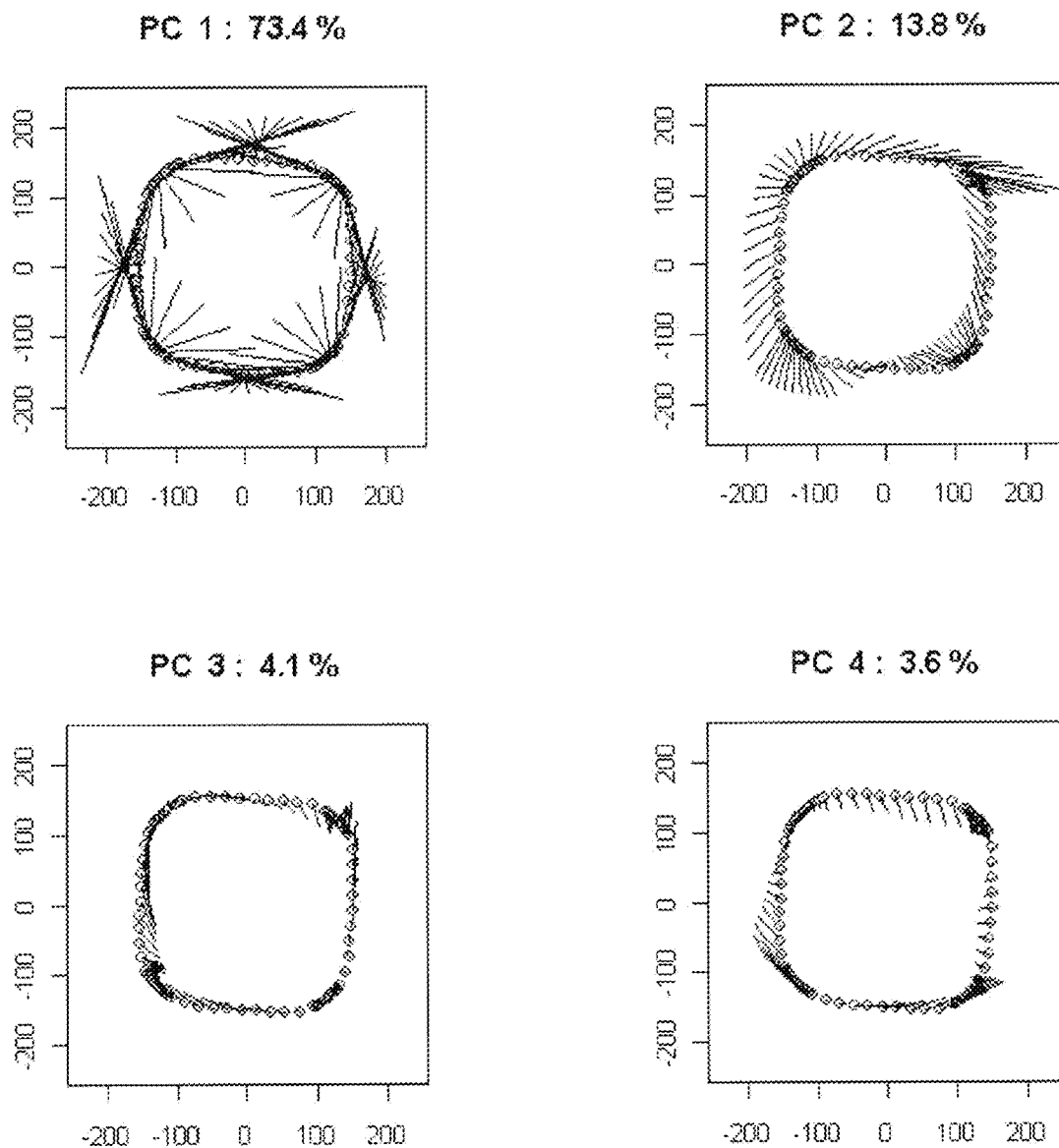
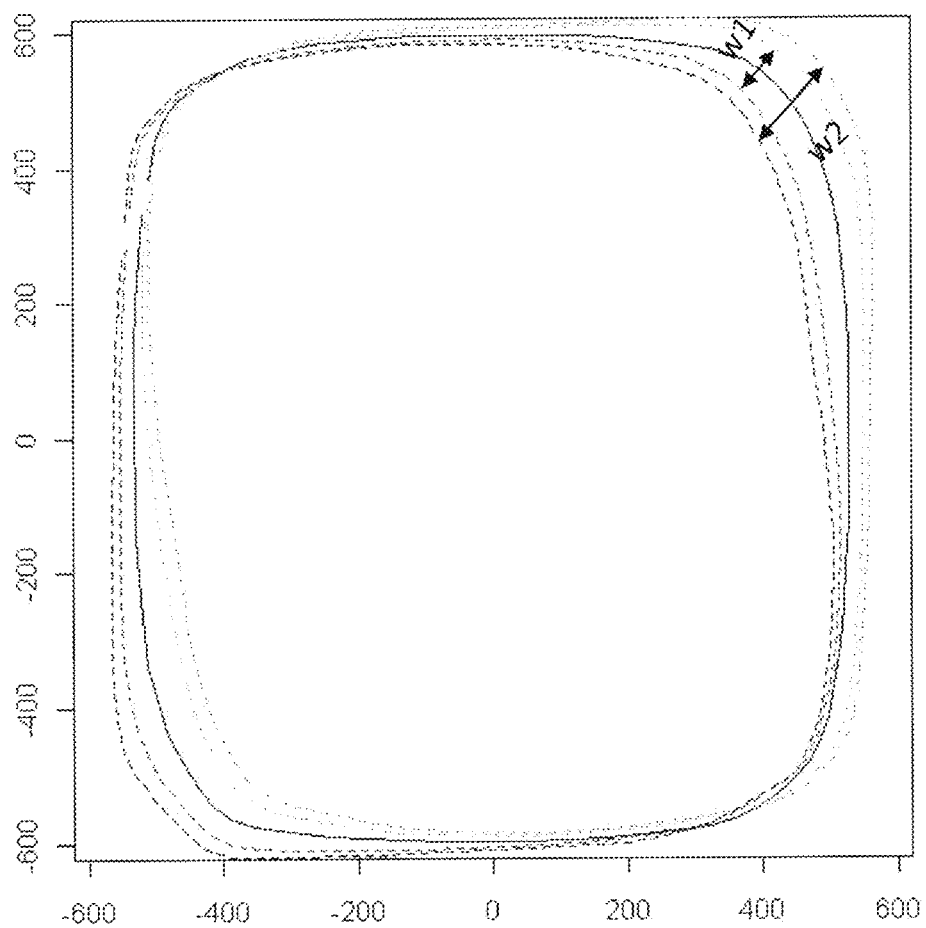


FIG. 8



1

SHAPE METROLOGY FOR PHOTOMASKS**BACKGROUND**

The manufacturing of semiconductor devices includes the transfer of patterns into the semiconductor wafer in a photolithography process. Shortwave radiation from a laser source passes a photomask or is reflected at a photomask and incidents on a photosensitive layer on the semiconductor wafer. The pattern of the photomask defines the pattern on the semiconductor wafer. There is a need to supply semiconductor manufacturers with photomasks reliably fulfilling imaging specifications with respect to the imaged patterns.

SUMMARY

According to an embodiment a method of manufacturing a photomask includes forming a mask pattern that includes a critical mask feature on a photomask. Shape information which is descriptive for an outline of the critical mask feature is obtained from the photomask. The shape information contains position information identifying the positions of landmarks on the outline relative to each other.

According to another embodiment, a photomask package includes a photomask with a critical mask feature as well as shape information descriptive for an outline of the critical mask feature on the photomask. The shape information contains position information identifying the positions of landmarks on the outline relative to each other.

According to a further embodiment, a method for evaluating a photomask includes obtaining shape information descriptive for an outline of a critical mask feature on the photomask. The shape information contains position information identifying the positions of landmarks on the outline relative to each other. The landmarks indicate at least one of local curvature extrema, points of inflexion, sharp bends in the curvature and local curvature-change maxima in the outline of the critical mask feature, respectively.

Those skilled in the art will recognize additional features and advantages upon reading the following detailed description and on viewing the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings are included to provide a further understanding of the invention and are incorporated in and constitute a part of this specification. The drawings illustrate the embodiments of the present invention and together with the description serve to explain principles of the invention. Other embodiments of the invention and intended advantages will be readily appreciated, as they become better understood by reference to the following detailed description.

FIG. 1A is a schematic diagram of an appliance including a semiconductor wafer for illustrating a method of manufacturing a photomask according to an embodiment.

FIG. 1B is a schematic diagram showing a photomask package according to a further embodiment.

FIG. 1C is a schematic diagram of an appliance including a photomask and a semiconductor wafer for illustrating a method of manufacturing semiconductor devices using a photomask in accordance with a further embodiment.

FIG. 1D is a schematic diagram of an appliance based on a photomask package and including a semiconductor wafer for illustrating a method of manufacturing semiconductor devices according to an embodiment related to OPC (optical proximity correction) using shape information of critical features on a photomask.

2

FIG. 2A is a schematic diagram of a mask feature for illustrating the specification of mask features by fitting long parallel lines for discussing effects of the embodiments.

FIG. 2B is a schematic diagram of a mask feature for illustrating the specification of mask features by fitting short parallel lines for discussing effects of the embodiments.

FIG. 3A is a schematic diagram showing corner rounding as an example for shape variations for discussing effects of the embodiments.

FIG. 3B is a schematic diagram showing end shortening as an example for shape variations for discussing effects of the embodiments.

FIG. 3C is a schematic diagram plotting a fitting error against the contact size for discussing effects of the embodiments.

FIG. 4A is a schematic diagram showing contact outlines for illustrating conventional contact metrology and discussing effects of the embodiments.

FIG. 4B is a schematic diagram showing contact outlines for illustrating a contact shape metrology according to an embodiment.

FIG. 5A is a schematic plan view of a square target feature and a corresponding mask feature for illustrating the selection of first landmarks according to an embodiment.

FIG. 5B is a schematic plan view of a square target feature and a corresponding mask feature for illustrating the selection of second landmarks according to another embodiment.

FIG. 5C is a schematic plan view of a U-shaped target feature for illustrating the selection of landmarks according to a further embodiment concerning U-shaped patterns.

FIG. 6 is a schematic diagram illustrating the selection of landmarks according to a further embodiment.

FIG. 7A is a schematic plan view of a field of mask features corresponding to square target features for contact pads for discussing effects of the embodiments.

FIG. 7B is a schematic plan view of a set of diagrams showing a field of mask features corresponding to square target features for contact pads for discussing effects of the embodiments on contact linearity.

FIG. 7C is a schematic plan view of a set of diagrams showing results of a PCA (principal component analysis) of the mask features of FIG. 7B.

FIG. 8 is a schematic diagram illustrating shaped confidence intervals for mask features corresponding to a square target feature for discussing effects of the embodiments.

DETAILED DESCRIPTION

In the following detailed description, reference is made to the accompanying drawings, which form a part hereof, and in which are shown by way of illustrations specific embodiments in which the invention may be practiced. It is to be understood that other embodiments may be utilized and structural or logical changes may be made without departing from the scope of the present invention. For example, features illustrated or described for one embodiment can be used on or in conjunction with other embodiments to yield yet a further embodiment. It is intended that the present invention includes such modifications and variations. The examples are described using specific language which should not be construed as limiting the scope of the appending claims. The drawings are not scaled and are for illustrative purposes only. For clarity, the same elements have been designated by corresponding references in the different drawings if not stated otherwise.

The terms "having", "containing", "including", "comprising" are open and the terms indicate the presence of stated

3

structures, elements or features but not preclude additional elements or features. The articles “a”, “an” and “the” are intended to include the plural as well as the singular, unless the context clearly indicates otherwise.

FIG. 1A shows a photomask **110** including a mask pattern with one or more critical mask features **111**. The photomask **110** may be a reflective mask with the mask pattern formed by absorbent and reflective sections or a transparent mask with the mask pattern including transparent and opaque sections. The critical feature **111** may be a reflective or absorbent feature on a reflective mask or an opaque or transparent feature in a transparent mask.

An inspection unit **210** retrieves shape information **120** of at least one critical mask feature **111** from the photomask **110** and transfers the shape information **120** to a data storage unit **310**. The shape information **120** contains information about the outline (contour) of the critical feature **111**. The shape information **120** may contain position information of prominent points (landmarks) on the outline, wherein at least one or some of the landmarks are not assignable to a rectangular approximation of the mask feature. From the position information of the landmarks both more precise areal information of the critical feature **111** on the photomask **110** and details descriptive for a type of contour deviation from the target outline may be obtained.

Conventionally, information descriptive for a photomask may contain statistical CD (critical dimension) information about a minimum width, mean width and maximum width of the critical feature **111** along one lateral axis or along two orthogonal lateral axes. By contrast, the shape information **120** according to the embodiments may contain statistical information descriptive for the deviation of the contour of the critical mask feature **111** from a target contour with respect to more than two horizontal axes. While conventional CD information may describe the deviation of a size of a rectangular approximation of an actual mask feature from the size of a rectangular target feature, the shape information **120** describes the deviation of an outline of the mask feature from the outline of the a mean mask feature or a target feature. An area of the critical mask feature can be more precisely calculated on the basis of the shape information **120** than on the basis of a rectangular approximation. The shape information **120** may contain information describing a type and degree of shape variation such as edge bowing, line shortening, and/or corner rounding, by way of example. In addition the shape information **120** may include statistical information of variation patterns descriptive for the type and degree of a deviation of the outlines of mask features from a mean shape of a plurality of mask features corresponding to the same target feature.

As regards lines of closely spaced contacts information concerning a distance between the contacts along the contact line may be more relevant than the information about how the contacts expand or shrink along the direction perpendicular to the contact line. According to an embodiment, the critical mask feature **111** may be a line of isolated mask features resulting from a line of isolated square target features, or the spaces therebetween. Another critical feature may be given by two adjacent lines with rectangular bulges opposite to each other, where the line fitting approximation relies on only few values because the fitting process neglects sample points close to the edges of the bulges and the absolute number of sample points is low. Instead, with the shape information **120** the critical feature can be characterized by more and/or more significant sample points allowing a precise estimation of whether or not the photomask may be used for the intended purpose.

4

The method provides a photomask package **100** including the photomask **110** and the shape information **120** to a user as illustrated in FIG. 1B. The data storage unit **310** may be any kind of portable data carrier or a server accessible for the user of the photomask **110**. The user of the photomask **110** may access the data storage unit **310** to obtain the shape information **120** for critical mask features **111** and to control an illumination process using the photomask **110** by adapting an illumination parameter, e.g. a defocus and/or illumination intensity, according to the shape information **120**.

According to another embodiment the shape information **120** may be compared with target shape information of the concerned critical features **111**. The result of the comparison may be used to discard or rework photomasks **110** that do not fulfil specifications set up by the user of the photomask **110**. If the shape information **120** complies with the target shape information, a process for manufacturing semiconductor devices or micro electromechanical systems may use the photomask **110** to transfer the mask pattern into a radiation sensitive layer, e.g., a photoresist layer **310** on a semiconductor wafer **300** as illustrated in FIG. 1C.

According to a further embodiment illustrated in FIG. 1D, an optical proximity correction unit **220** may combine the shape information **120** about the critical features **111** of a mask pattern and layout data **320** describing the mask pattern of a photomask **110** in an extended optical proximity correction algorithm. The extended optical proximity correction algorithm may calculate optical proximity features using the shape information **120** such that a further photomask **110x** with updated optical proximity features can be obtained that more precisely fulfils the photomask specifications and the requirements of a target lithography process. The process may be reiterated to further improve the imaging properties.

Compared to conventional approaches, which obtain and evaluate rectangular approximations of critical features **111**, the shape information **120** more precisely expresses whether or not the photomask **110** fulfils the requirements of a target lithography process. In addition, the shape information **120** provides more reliable information about further critical properties of the mask features such as area and minimum width of critical mask features **111** as well as minimum distances between selected mask features.

FIGS. 2A and 2B refer to a line **111a** as an example for a critical mask feature. The target shape of the line **111a** is a rectangle with a target line width **W1**. Due to process imperfections and proximity effects the corresponding actual shape **111b** on the photomask is not rectangular but may be rounded, distorted and shortened and the line edges may be undulated instead of straight. Typically, an average width of the actual shape **111** on the photomask is estimated for deciding whether the photomask fulfils a given specification. For this purpose, an optical measurement apparatus uses a line fitting approach that approximates the distorted line edges by two parallel auxiliary lines **401**, **402** and then outputs the distance between the two auxiliary lines **401**, **402** as an estimation for an average line width **WF1**. A plurality of critical features on the photomask may be evaluated, for example, for deciding whether or not the photomask fulfils predefined requirements concerning CDU (critical dimension uniformity).

The auxiliary lines **401**, **402** average the respective edges of the actual line **111b** within a measurement window with a window length **LF**. When the target line width **W1** is in the range of the absolute critical dimensions for the photomask, the fitting of the two parallel auxiliary lines **401**, **402** for obtaining an approximation of the actual average line width **WF1** of critical mask features depends on the window length **LF**.

In FIG. 2A the auxiliary lines **401**, **402** are comparatively long and the result of the line fitting may pretend a sufficiently wide approximated average line width **WF1** though the distortions may locally reduce the actual line width significantly to below the approximated average line width **WF1**.

In case the line **111a** corresponds to a connection line, the resistivity of the connection line strongly depends on the contour of the line **111a**. Though the result of a line fitting approach may pretend that the line **111a** fulfils a given width criterion, a conductive line obtained from the line **111a** by a lithography process using the photomask with the line **111a** may have a higher resistance than desired. In addition, resist fins obtained by developing the photo sensitive film after exposure may tend to collapse where the actual line width is significantly narrower than the approximated average line width **WF1**.

As shown in FIG. 2B, the measurement window for the line-fitting approach may have a smaller window length **LF** to get more relevant information on the line width **W1** using shorter auxiliary lines **411**, **412**. The smaller window length **LF** results in position-dependent approximations **WF1a**, **WF1b** for the average line width. The fitting algorithm needs a sufficient large number of points along the actual line **111b** to work, hence, a sufficiently long measurement window. But a long measurement window may conceal that the actual line width locally falls below a critical threshold within the measurement window **LF**.

FIG. 3A shows the effect of corner rounding. The target feature **112a** is a square and may correspond to contact pads or openings for contact vias in a target substrate such as a semiconductor wafer. At edge lengths **e1** greater than ten times the critical feature size **CD** of the respective mask, the shape of the actual mask feature **112b** appears nearly undistorted with regard to the target feature **112a** as illustrated on the left hand side. At an edge length **e1** approximating the critical feature size **CD**, the corners of the actual mask feature **112b** get increasingly rounded as illustrated in the central image. At an edge length **e1** close to the critical feature size **CD**, the actual mask feature **112b** approximates a circle as illustrated on the right hand side.

FIG. 3B shows the effect of corner rounding at line end portions. The target feature is a line **113a** that may correspond to a connection line or a line trench in a target substrate such as a semiconductor wafer. At line widths **LW1** greater than ten times the critical feature size **CD** of the respective mask, the shape of the actual line **113b** appears nearly undistorted with regard to the target line **113a** as illustrated on the left hand side. At a line width **LW1** approximating the critical feature size **CD**, the line end portion of the actual line **113b** gets increasingly shortened as illustrated in the central image. At a line width **LW1** close to the critical feature size **CD**, the corresponding actual line **113b** is significantly shortened and completely bowed as illustrated on the right hand side.

FIG. 3C shows a diagram plotting the CDU (critical dimension uniformity) against a contact size **CS** when using straight line fit, wherein a high CDU value indicates a high pattern variability. Below a certain contact size **CS 1** the fitting error **FE** increases the critical dimension uniformity and dominates the assessment of size variation.

FIG. 4A summarizes conventional contact metrology as an example for the application of conventional line fitting approaches. The conventional contact metrology assumes that the actual shape of the mask feature matches a target design **421**, which may be a rectangle as illustrated on the left hand side. Two orthogonal line fitting processes approximate the distance between the two pairs of opposing edges. The result is a pure scaling information describing a difference

between the area of the target design **421** and the approximated areas **422**, **423** given by the approximated lines edges as illustrated in the centre. In addition, mask features used in the context of SMO (source mask optimization) approaches may intentionally contain non-trivial mask features whose shapes are not based on straight, orthogonal lines. The line fitting approach approximates such mask features with rectangular patterns.

FIG. 4B illustrates a contact shape metrology based on the shape information **120** of FIGS. 1A to 1D. A mean shape **431** illustrated on the left hand side is computed from a plurality of mask features based on the same target feature. The target feature may be a rectangle or a non-trivial mask feature without straight edges. The mean shape **431** may correspond to one single target feature or a set of identical target features. Then variation patterns may be evaluated that describe the differences between single mask features and the mean shape **431**. The variation patterns may include information on the type of variation, for example rotation, scaling, and/or specific corner/edge distortion.

The upper illustration in the centre of FIG. 4B shows scaled shapes **432**, **433** resulting from the mean shape **431** by isotropic scaling. The variation pattern is isotropic scaling and the shape information may include information descriptive for the position of points on the outline of the mean shape **431** as well as an isotropic scaling factor. Further in the centre, FIG. 4B shows shapes **434a**, **434b** resulting from a variation pattern based on one-dimensional scaling of the mean shape **431**, wherein the scaling factor may depend on the direction of the scaling. Instead of or in addition to isotropic or one-dimensional scaling factors, the type of variation pattern may be rotation, specific corner distortion, and/or specific edge distortion and the shaping information may include information identifying the type of variation pattern as well as information identifying the scale of the respective variation pattern.

On the right hand side FIG. 4B illustrates local vectors **435** assigned to specific points on the contour of the mean shape **431**. Modifications of the mean shape **431** can be expressed by assigning to each local vector **435** a length and a direction. The shape information may include information descriptive for the position of points on the outline of the mean shape **431** as well as statistical information about position, length and direction of the local vectors **435**, the latter being descriptive for the variation pattern.

Prominent points on the outlines of the mean shape and the mask features are selected to describe the mean shape **431** and may serve as bases for the description of the variation patterns using the local vectors **435**. The points include first landmarks (mathematical landmarks) and may further include, if applicable, second landmarks (interpolated or constructed landmarks). The first landmarks are defined by a geometric property of the outline at the concerned landmark. For example, the first landmarks may indicate at least one of local curvature maxima, local curvature minima, extreme points and points of inflexion, by way of example. The position of a second landmark on the outline does not directly indicate a specific geometric property of the concerned outline but is derived from the position of the first landmarks.

On the basis of their geometrical properties, a landmark recovery process identifies the first landmarks on the actual mask features and calculates a mean shape with respective mean positions of corresponding landmarks. A variation pattern included in the shape information may describe how the positions of the landmarks relative to each other change between the calculated mean shape and the respective actual mask features. The variation patterns may be described by the

principal components of a PCA on the basis of a plurality of mask features obtained from the same target feature on different mask positions and/or differently scaled target features.

FIG. 5A refers to first landmarks on mask features resulting from square target features that may be intentionally non rectangular mask features. On the left hand side FIG. 5A shows first target landmarks **441** located in the corners of a square target feature **451**. On the outline of a corresponding actual mask feature **452** a landmark recovery process may identify first image landmarks **455** that may correspond to the first target landmarks **441** with respect to their geometric properties. A correspondence between the first target landmarks **441** and the first image landmarks **455** may be a one-to-one correspondence.

For the illustrated example, two first image landmarks **455** on the actual mask feature or mean shape **452** are assigned to each of the first target landmarks **441**, respectively, as illustrated on the right hand side of FIG. 5A. On the outline of a corner-rounded mask feature the first image landmarks **455** may be identified at transitions points between straight and bowed sections or at points, where a first or second derivative of a positional function defined in a Cartesian coordinate system aligned to the edges of the target feature **451** has a sharp bend, a step or a local extremum.

FIG. 5B refers to embodiments for the selection of second landmarks on mask features resulting from square target features that may be intentionally non rectangular mask features. The positions of the second target landmarks **442** are derived from the positions of the first target landmarks **441**. On the left hand side groups of second target landmarks **442** are located between two neighboring first target landmarks **441** of a square target feature **451**, respectively. The number of second target landmarks **442** between two first target landmarks **441** may vary, e.g., may be a function of the distance between the two concerned first target landmarks **441**. According to the illustrated embodiment, the number of second target landmarks **442** is the same between each pair of neighboring first target landmarks **441**. The distance between second target landmarks **442** assigned to the same group and to the respective first target landmarks **441** may vary. According to the illustrated embodiment, the first and second target landmarks **441**, **442** are equidistant on the target feature **451**.

The landmark recovery process may identify second image landmarks **456** that may correspond to the second target landmarks **442** with respect to their relative position to each other. For example, after identifying the first image landmarks **455**, the landmark recovery process may divide an outline section between neighboring first image landmarks **455** assigned to different first target landmarks **441** into equidistant portions according to the number of second target landmarks **442** in the concerned outlined section. The correspondence between the second target landmarks **442** and the second image landmarks **456** may be a one-to-one correspondence.

The target features may be squares or rectangles with or without rounded corners, stripes, ovals, non-trivial mask features without straight edges or more complex structures such as specific line patterns. In FIG. 5C the target feature **451** is a portion of a U-shaped line as illustrated on the top of FIG. 5C. The corners may define the first target landmarks **441**. The landmark recovery process identifies the first image landmarks **455** as illustrated in the center. A further evaluation may be based only on the relative position of the first image landmarks **455** in a region of interest **460** as illustrated at the bottom of FIG. 5C and the corresponding variation pattern,

whereas further shape information as regards the target feature **451** outside the region of interest **460** may be neglected or discarded.

Critical features evaluated in conventional approaches like line fitting are typically provided as test patterns in non-producing portions of the photomask. But shape deviations like edge variation and contact rounding depend on the context of the concerned feature. Therefore photomasks that do fulfill the specification with regard to the test patterns might fail at the user side because the test pattern is not appropriate to give enough information about critical areas within the producing mask portions. Other photomasks may not fulfill the specifications for the test pattern but would fulfill user's requirements within the producing mask portion.

In addition, line fitting appears not to be appropriate where the basic assumption of pattern fidelity, e.g. that the actual mask features for rectangular target features are rectangular does not fit and where shape variations become dominant.

Instead, the shape information gives to the user more relevant information on how the features on the mask behave and how the features are imaged into a target substrate.

Assumed a previously approved process for manufacturing a photomask is changed, e.g. by changing a developer solution. Even if the new process results in photomasks fulfilling the specification as regards a test pattern, there is still some risk that the new process does not fit for specific structures in the producing portion of the photomask. Since the method according to the embodiments may compare more detailed shape information on features in the producing portions of the photomasks obtained by the old and new processes, respectively, the risk for delivering not-approvable photomasks is significantly reduced when a parameter of the manufacture process changes.

FIG. 6 refers to a landmark recovery process which may identify first landmarks on the outline of actual mask features.

An optical device scans or images the photomask, e.g., by SEM (scanning electron microscopy). An edge detection process identifies the outlines of the photomask and may detect points **602** on the outline of a mask feature. An estimation process may approximate an outline estimation **604**, which may be described as a positional function $f(x,y)$ of two orthogonal coordinate values x, y using, e.g. a method minimizing a means square error of the points **602** with regard to the outline estimation **604** given by the positional function $f(x,y)$. Local maximum and/or minimum values of the first and second derivations $d_2f/dx^2, d_2f/dy^2$ of the positional function may identify first image landmarks **441** where the outline and/or a concavity of the outline estimation **604** have local minima or local maxima. According to the illustrated embodiment first image landmarks are identified where second derivatives of the outline estimation **604** with respect to two orthogonal axes have local extrema, respectively.

With the knowledge about the position of the landmarks **441**, **442** relative to each other and about the variation patterns describing direction and an amount of a displacement of the landmarks with respect to their mean positions, an evaluation program or evaluation unit may more precisely estimate, e.g., an area variation of the squared mask feature as well as minimum, mean and maximum distances of the actual mask features with respect to any lateral axis.

In a similar way, minimum widths of lines and minimum distances between neighbouring lines on the photomask can be more precisely defined. Photomasks, which according to conventional line-fitting approaches masks do fulfil a specification defined with regard to a test pattern can fail at the client side because either the test pattern is not appropriate to give enough information about critical areas within the pro-

ducing mask area or the fitting algorithm loses critical information, for example on a minimum line width. On the other hand photomasks that do not fulfil the specifications obtained on the test pattern by conventional line fitting approaches may nevertheless fulfil client's requirements within the producing mask area, for example where the line fitting algorithm indicates smaller contact areas than actually provided by the mask.

Using the shape information more masks with critical line deviations can be discarded or reworked at an early stage of the process and more masks that are actually suitable for manufacturing semiconductor devices can be saved from falsely being discarded. The shape metrology increases efficiency in the field of photomask manufacture. In addition, the shape metrology according to the embodiment may handle non-trivial mask features. The methods of statistical shape analysis can be used for CD analysis, contact area analysis etc. Shape changes can be classified, quantified and measured.

FIG. 7A refers to local contact uniformity and shows a group of mask features that may correspond to a group of square target features described in source layout data of the photomask, wherein the target features have identical dimensions. A landmark recovery process may recover the positions of the image landmarks in each of the mask features. The position information about corresponding image landmarks in the actual square mask features may be combined, respectively, and a set of combined image landmark information may provide position information about mean image landmarks on the outline of a mean shape of the mask features.

FIG. 7B refers to contact linearity and shows three sets of mask features that may correspond to three sets of square target features of different size described in source layout data of the photomask. A landmark recovery process recovers positions of the image landmarks in each of the mask features.

A PCA (principal component analysis) may be performed for each set of corresponding landmarks. The PCA converts the position deviations of corresponding landmarks into a set of values of linearly uncorrelated principal components.

FIG. 7C shows the result of the PCA for the data set of FIG. 7B. The measures obtained by SEM may be used to calibrate the average area of the mask features. For example, a normalized centroid size $NS(x)$ may be given by equation (1).

$$NS(x) = \frac{\sqrt{\sum_{i=1}^k \sum_{j=1}^m (x_{ij} - \langle x_j \rangle)^2}}{\sqrt{km}} \quad (1)$$

In equation (1), k is the number of landmarks and m the number of dimensions. The mean shape and the variations of the mask features may be computed based on minimizing the square distance of the mean shape or maximizing the likelihood of the mean shape, by way of example.

If the data describing the outline of the mask features is available in the form according to equation (2).

$$w_i = \gamma_i 1_k + \beta_i \exp(i\theta_i)(\mu + \epsilon_i) \quad i=1, \dots, n \quad (2)$$

With w_i indicating the vector of one pattern realization, γ_i indicating the translation, 1_k indicating a unit $k \times k$ matrix, β_i indicating the scaling, θ_i indicating the rotation, μ indicating the population mean configuration and ϵ_i indicating an uncorrelated normal distributed residual, the mean shape $[\mu]$ is found by equation (3).

$$[\mu] = \arg \inf_{\mu} \sum_i d^2(w_i, \mu) \quad (3)$$

In (3) d is the distance measure and μ is an unknown unit size mean configuration.

Differences between the mean image landmarks and the respective actual image landmarks along the outlines of the actual square mask features deliver statistical information from which the behavior of further mask features may be estimated. A variation pattern given by the differences between the mean image landmarks and the landmarks in the target feature delivers information of a variation pattern and/or variation degree descriptive for the sort and/or degree of deviation from the target features.

FIG. 8 shows a mean mask feature 431 in a photomask evaluated using shape information as discussed above. The statistical evaluation reveals that 90% of the actual mask features have outlines within a first strap S1 and 95% of the actual mask features have outlines within a second strap S2. This information may be more relevant to the user of the photomask than conventional CD information along two axes. The user may use the shape information to decide whether the photomask is used in a process for manufacturing micromechanical or semiconductor devices. Alternatively, the user may use the shape information to amend suitable optical proximity correction features that at least partly compensate for a variation pattern identified in a first photomask to produce a second photomask with a more realistic imaging pattern.

What is claimed is:

1. A method of manufacturing a photomask, the method comprising:

forming a mask pattern including a critical mask feature on a photomask; and

scanning or imaging the photomask to optically retrieve, from the photomask, shape information descriptive for an outline of the critical mask feature on the photomask, wherein the shape information contains position information identifying the positions of isolated landmarks on the outline relative to each other and wherein first ones of the landmarks indicate at least one of local curvature extrema, points of inflexion, sharp bends in the curvature and local curvature-change maxima in the outline of the critical mask feature, respectively.

2. The method of claim 1, further comprising: delivering the photomask in combination with the shape information.

3. The method of claim 2, further comprising: comparing the obtained shape information with reference shape information descriptive for a target shape of the critical mask feature with respect to a predetermined criterion.

4. The method of claim 3, further comprising: using the photomask for illuminating semiconductor wafers in the course of a semiconductor production process if the obtained shape information fulfills the predetermined criterion and, otherwise discarding or reworking the photomask.

5. The method of claim 1, further comprising: comparing the obtained shape information with reference shape information descriptive for a target shape of the critical mask feature with respect to a predetermined criterion.

6. The method of claim 1, wherein second ones of the landmarks are defined at predefined positions of the outline between neighboring first landmarks.

11

7. The method of claim 1, wherein
first ones of the landmarks indicate at least one of zero-
crosses and steps in a second derivative of the outline of
the critical mask feature, respectively. 5
8. The method of claim 1, wherein
the shape information contains mean shape information
descriptive for a mean outline of a set of critical mask
features assigned to a same target outline and statistical
information on deviations of the critical mask features of 10
the set from the mean outline.
9. The method of claim 8, wherein
the critical mask features are in a productive portion of the
photomask. 15
10. The method of claim 8, wherein
the statistical information on deviations refers to the land-
marks.
11. The method of claim 8, wherein 20
the statistical information is based on a principal compo-
nent analysis of the statistical information.

12

12. The method of claim 1, further comprising:
using the shape information in a method for optical prox-
imity correction to obtain information describing optical
proximity correction features suitable for enhancing a
process window for a target feature on a semiconductor
photomask, wherein the target feature corresponds to the
critical mask feature.
13. A method of evaluating a photomask, the method com-
prising:
scanning or imaging the photomask to optically retrieve,
from the photomask, shape information descriptive for
an outline of a critical mask feature on the photomask,
wherein the shape information contains position infor-
mation identifying the positions of landmarks on the
actual outline relative to each other; and
defining the landmarks to indicate at least one of local
curvature extrema, points of inflexion, sharp bends in the
curvature and local curvature-change maxima in the out-
line of the critical mask feature, respectively.

* * * * *